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OPTIMIZING TUNED AUXILIARY STRUCTURES FOR POWER HARVESTING

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ABSTRACT

Sensor systems used for structural health monitoring and damage prognosis applications are often limited by the lifetime or connectivity of their power sources. By harvesting power from ambient sources it is possible to overcome these constraints and develop autonomous, self-contained sensor systems. This study investigates the prospect of capturing ambient vibration energy using piezoelectric material. Specifically, modal analysis techniques will be employed to optimize the vibration energy available to a lead zirconate/lead titanate (PZT) element adhered to an auxiliary cantilever beam structure. This will involve varying the geometry of the auxiliary structure, varying its location on the host structure, and tuning the auxiliary structure to selected resonant frequencies of the host structure.

INTRODUCTION

The concept of using piezoelectric materials in power harvesting, or the conversion of non-electrical energy into electrical energy, has been an increasingly popular research topic since the mid-1990's. Piezoelectric materials exhibit electromechanical coupling, which means that the application of voltage to the material will deform the material along a certain axis; likewise, straining the material will cause the material to produce a voltage. Many setups have been developed to harness this voltage in an effort to perform useful tasks. For example, two types of shoe inserts have been developed using piezoelectric material to capture some of the energy associated with walking [1]. These piezoelectric inserts produced a maximum average power of 8.4 mW, which was used to power an active radio frequency tag that transmitted a short-range 12-bit wireless identification code while the user walks. In Ref. [2], harvesting the energy of microwave oven vibrations to power small wireless sensor nodes was investigated. In another example, harvested power from simulated car engine vibrations was used to charge batteries [3]. Many more applications of power harvesting through the use of piezoelectric materials are currently being investigated [4,5,6].

In this study, the results of a previous study of power harvesting using tuned auxiliary structures are extended. In Ref. [7], a tuned vibration absorber was used to maximize the power available to be harvested using a PZT patch. The auxiliary structure used was an aluminum cantilever beam, and it was attached to the host structure at a fixed position for the duration of the experiments. The beam was tuned to three dominant natural frequencies of the host structure by adding different masses to the free end of the beam. Identical piezoelectric patches were attached to the host structure and tuned and un-tuned versions of the cantilever beam. The host structure was excited with a broadband white noise, and the open-loop RMS (root-mean-square) voltage and maximum power produced by the piezoelectric materials were measured. Many parameters in this previous study were held constant, such as the geometry and material of the beam, the location of the beam on the host structure, and the size of the piezoelectric patches. The setup produced a maximum open-loop voltage of 0.473 V_{rms} and a maximum power of 0.1 μW using white noise excitation. Clearly, higher output is necessary for practical applications.

For this auxiliary beam optimization study, the same host structure was used as in Ref. [7], but more parameters were varied. The host structure can be seen in **Error! Reference source not found.** below. The modal characteristics of the host structure were first reanalyzed in order to determine any differences in the frequencies of the structure from when it was previously tested. Two natural frequencies of the host structure were then chosen for study. Multiple cantilever beams, both uniform and with end masses, were tuned to each of these two chosen natural frequencies. Therefore, the effect of different beam geometries could be examined. The beams were also placed at different locations on the host structure to determine which location would produce the most output. These factors were examined to determine which configuration would allow the auxiliary structure to absorb the most vibrational energy.

Figure 1: Power harvesting host structure.

THEORY

Power output from PZT

Figure 2 shows a schematic of the cantilever beam with the PZT attached.

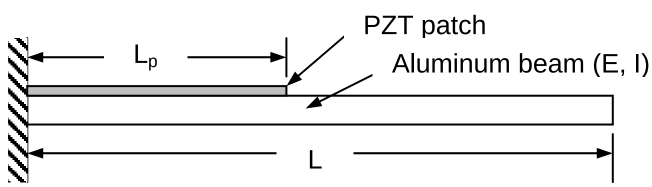


Figure 2: Side view of cantilever beam auxiliary structure with PZT.

In Ref. [7], the voltage output from the PZT in this setup was found to be approximately described by

$$V_{out}(t) = \frac{K_s \phi_{na} \phi_{nk} F}{2EI}\left(2LL_p - L_p^2\right), \tag{1}$$

where
V_{out} = the output voltage from the PZT,
K_s = a term depending on the properties and geometry of the PZT, constant for all tests conducted here,
ϕ_{na} = the magnitude of the n^{th} mode at the location of the auxiliary structure,
ϕ_{nk} = the magnitude of the n^{th} mode at the location of the force input,
F = the input force,
E = the elastic modulus of the cantilever beam auxiliary structure,
I = the area moment of inertia of the cantilever beam auxiliary structure,
L = the length of the cantilever beam auxiliary structure, and
L_p = the length of the PZT patch.

See Ref. [7] for the complete derivation. This equation contains many assumptions, for example, it assumes that the auxiliary structure and the host structure can both be modeled as single-degree-of-freedom systems. In spite of these assumptions, it may still be used to make several observations. First, the output from the power harvesting system should depend on the mode shape magnitude at both the location of the auxiliary structure and the location of the excitation. This assumes, however, that the auxiliary structure is responding only to the mode to which it is tuned, and is experiencing only first bending deflection, which may not be the case. It can also be seen that increasing the input force will increase the voltage output. Overall, the geometry of the auxiliary beam should be designed to maximize the strain in the PZT.

Note that end masses were used to tune the beams in Ref. [7]. The derivation above, taken from Ref. [7], does not account for the end mass and was derived for a uniform cantilever beam.

Natural frequency of cantilever beam

Designing the auxiliary structures required estimating the dimensions necessary to achieve a given first natural frequency. Given the material properties and the specified frequency, this can be done using [8]

$$L = \sqrt[4]{\frac{EI}{\mu\left(\frac{\omega_n}{3.52}\right)^2}}, \tag{2}$$

where
E = Young's modulus,
I = area moment of inertia,
L = length of beam, and
μ = mass per unit length of beam.

EXPERIMENTAL SETUP

The power harvesting structure, shown in **Error! Reference source not found.**, was approximately 1.5 meters (5 feet) tall. It consisted of four aluminum plates bolted to four aluminum columns using right-angled steel brackets. The structure was supported at the bottom by four inflatable air bearings. Before the actual tests were performed, the cantilever beam tuned absorbers were designed and fabricated. The basic setup for the tests on the host structure was then developed, and the possible methods for quantifying the performance of the power harvesting system were investigated as discussed below.

Design of tuned absorber auxiliary structures

The tuned absorbers used were simple cantilever beams, as shown in Figure 3.

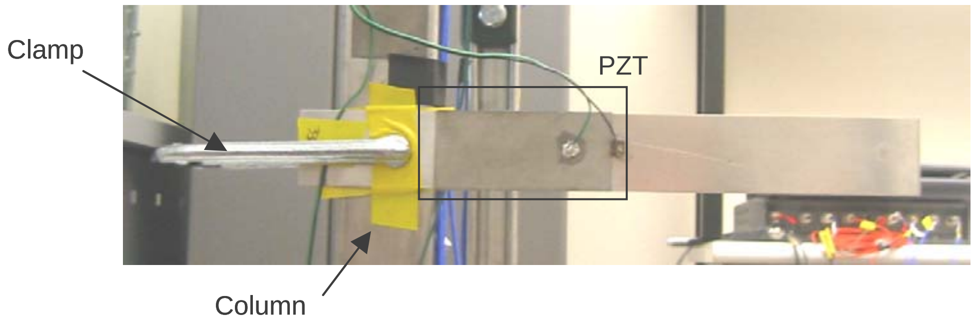


Figure 3: Cantilever beam tuned absorber, clamped to structure column.

Each beam was designed to have a first natural frequency that matched a resonant frequency of the host structure. To reduce the number of factors under consideration, all beams had the same width and the same size PZT attached to them. Based on the desired first natural frequency, material properties, and beam thickness, the necessary active beam length, *L*, can be calculated using Eq. (2).

There was concern about whether the short beams could be considered "beams," since their length-to-width ratio was fairly low. A simple finite element model was developed for one of these short beams, and it was found that the first natural frequency was sufficiently close to the frequency predicted by the beam equation.

Two different host structure resonant frequencies were considered: 33.0 Hz and 40.5 Hz. Two different thicknesses of aluminum were used to manufacture beams, resulting in a total of 4 different beam types.

A PSI-5H4E PZT patch from Piezo Systems was adhered to the base of each beam. Each patch was 3.18 cm (1.25 inches) wide by 7.24 cm (2.85 inches) long. This size is the same as that used in Ref. [7]. The PZT's were attached to the beams using Dr. Bond Super Glue, and were clamped in place until the glue had set.

Test method

To conduct each test, the auxiliary structure was first attached to a column of the structure with a C-clamp, as shown in Figure 3. The length of the beam with respect to the edge of the column was adjusted so that the desired frequency was reached. Thus, for different beams, the location of the PZT element relative to the edge of the column was not constant, which may be a source of error. The effect of using a small shim between the beam and the clamp was also tested, but it was not found to have a significant effect on the first natural frequency of the beam or its power harvesting performance. The direction of the host structure's deflection for each mode was known, since it was determined from a modal test. To best harness the structure's vibrational energy, the cantilever beam was placed so that it would deflect in the same direction as the host structure. The structure was then excited with a shaker, in this same direction, with a 1 V_{rms} white noise input. The voltage across the PZT, the frequency spectrum of this signal, and the input from the shaker were recorded using an 8-channel, 24-bit Dactron Spectrabook FFT analyzer that was controlled by a PC running *RT Pro SB* software.

Quantifying PZT output

Two methods for quantifying the output from the power harvesting system were considered. The first, and simplest, method is to measure the open-loop voltage across the PZT. The time history of this signal can be recorded and the RMS value can be determined. The second available method is to measure the power output of the PZT by connecting a resistor to the PZT and measuring the voltage across this resistor. This method involves using a potentiometer to adjust the resistance to achieve maximum power. While the power is ultimately what is of interest, it is much more time consuming to measure and it was believed that for identical PZT elements, measuring the open-loop voltage would be sufficient.

A simple test was therefore conducted to determine whether open-loop voltage and power follow the same trend. This would mean that the best-performing beam could be identified by simply measuring the voltage generated by the PZT. Three tests were conducted in which the beam locations and geometries were chosen so as to vary as many parameters as possible, and the open-loop voltage and power output were found for each. (More details – how did you choose the locations, possibly show a power vs. resistance plot if you have the data) The results show that the two types of measurements do follow the same trend, as can be seen in Figure 4.

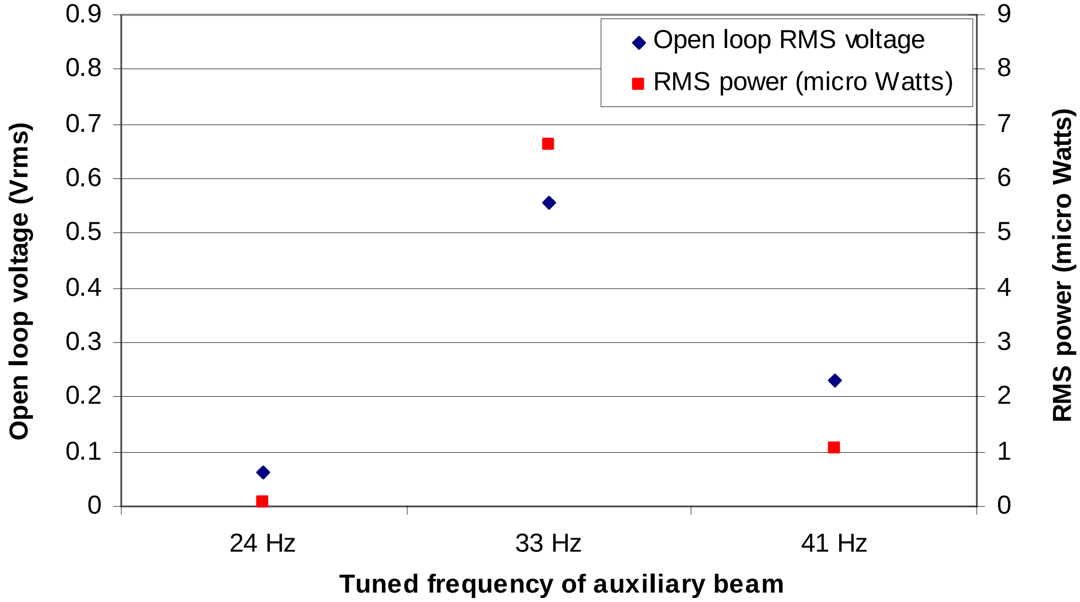


Figure 4: Three sample tests to verify open-loop voltage and power follow the same trend.

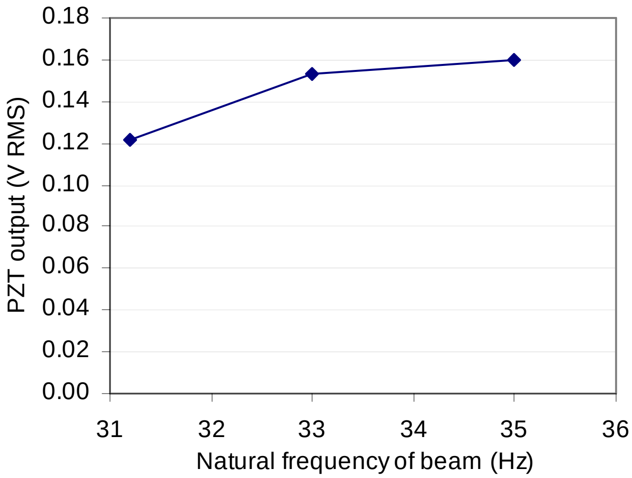
Therefore, open-loop voltage alone was used to compare the performance of the beams. For each data point, four 12-second samples were taken. The RMS value of each sample was found, and the four results were averaged.

RESULTS

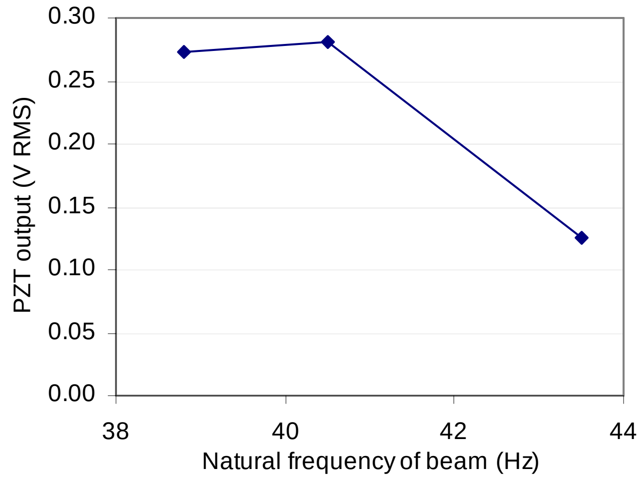
Tuning of beam

Although the beams were designed based on calculations of natural frequency, assuming the beams were truly cantilevered, the actual first natural frequencies of the beams varied slightly from the predicted values. This is most likely due to the stiffening of the beams resulting from the addition of the super glue and PZT elements, in combination with the fact that there may be some flexibility in the column and clamping so that the attachment point is not truly “fixed.” Each beam therefore had to be slightly retuned to match the desired frequency of the structure before tests could be conducted. This was accomplished by adjusting the free length of the beam with respect to the column as it was clamped to the structure. It should be noted that, due to the fact that it was difficult to predict the needed free length, the distance between the PZT and the edge of the column varied between –2.5 mm (meaning that the PZT slightly overlapped the column) and 11 mm.

It was of interest how critical this tuning was to the final output. If a tuned absorber power harvesting system of this type were put into use, it is possible that the frequency of the structure could not be exactly matched, due to practical requirements and possible shift of frequencies over time. Several tests were therefore conducted to determine how sensitive the output was to a slight mistuning of the beam. The 33 Hz beam was located at point 30 on the structure, while the 40.5 Hz beam was located at point 6. Each beam was tuned to three different frequencies near the resonance of the host structure, and the results are given in Figure 5.



a) Result of tuning on 33 Hz beam output



b) Result of tuning on 40.5 Hz beam output

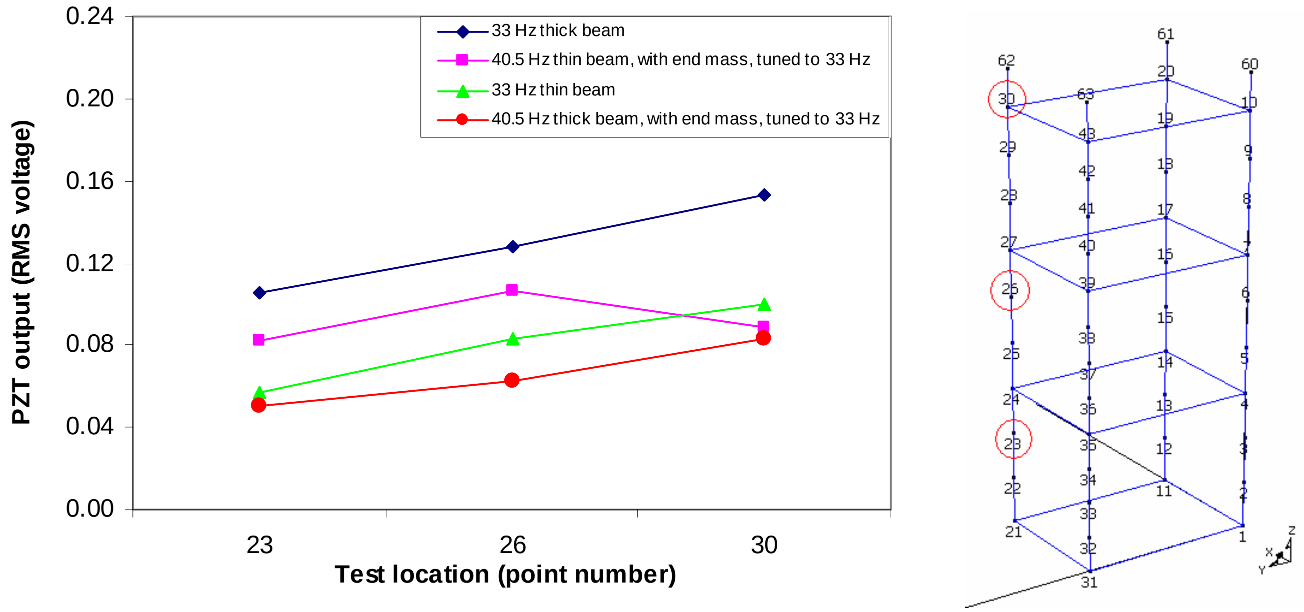
Figure 5: Comparison of tuned and mistuned beams.

For the 33 Hz beam, the slightly mistuned beam (tuned to 35 Hz) actually seemed to perform slightly better than the beam tuned to 33 Hz. This result is not yet understood, but it could be due to other frequencies present in the input to the PZT patch. For these tests, the two beams were placed at locations with high magnitude responses to their respective modes. For the 40.5 Hz beam, it was found that the tuned beam showed the best performance, as expected.

Auxiliary structure geometry

For a cantilever beam with a given first natural frequency, multiple designs are possible. Depending on the thickness and type of material chosen, the beam will have a different geometry. A certain frequency can also be matched by using a uniform cantilever beam with a higher first natural frequency, and adding an end mass to lower its frequency. To test the importance of beam geometry, several different beams having the same first natural frequency, but different designs, were tested. The results of testing each of the four different beams at three different locations are given in Figure 6a. The three test locations are shown in Figure 6b.

Aside from the final point of the thin beam with end mass, the results follow a clear pattern. Overall, the 33 Hz thick beam gave the best result, followed by the 40.5 Hz thin beam with the end mass. The most voltage was measured at point 30 in three of the four cases possibly because point 30 has the largest absolute magnitude response at the 33 Hz mode out of the three test locations. (See Figure 7 for the mode shape for the 33 Hz mode.) The 33 Hz thick beam produces a higher voltage than the 33 Hz thin beam possibly because the length of the thicker beam is longer. Revisiting Eq. (2), the voltage output from the PZT on the beam (V_{out}) is directly proportional to the length of the beam (L). Although increased thickness also increases the beam's area moment of inertia (I), it appears that increased length overrides the effect of increased area moment of inertia and leads to increased voltage. The 40.5 Hz thin beam tuned down to 33 Hz may produce a higher voltage than the 40.5 thick beam tuned down to 33 Hz possibly because the thinner beam required a larger end mass to be tuned down to 33 Hz. A larger end mass may result in larger deflections of the beam, and this may explain the higher voltage output from the 40.5 Hz thin beam. Further tests are planned to investigate these results, in particular to determine if the unusual result for the 40.5 Hz thin beam is repeatable.



(a) PZT output comparison for four different beam geometries (b) Test locations

Figure 6: Test results for beams with different geometries tuned to 33 Hz tested at three locations.

Relationship between mode shape magnitude and output

The effect of the location of the auxiliary beam on the host structure was next considered. It was assumed that the maximum output would be obtained from a beam placed at an antinode of the mode to which it was tuned. In other words, the greatest deflection of the host structure should result in the greatest output. In practice, however, it may not always be possible to place the tuned absorber on an antinode due to practical constraints. We wanted to determine whether placing the tuned absorber away from an antinode would have a significant effect on the power output. Both the 33 Hz and 40.5 Hz beams were tested.

The 33 Hz beam was tested at the seven different locations shown in Figure 7.

Figure 8a shows the relationship between the magnitude of the host structure's 33 Hz mode and the PZT output for the 33 Hz beam, and Figure 8b shows the relationship between the PZT output and the magnitude of the host structure's 40.5 Hz mode.

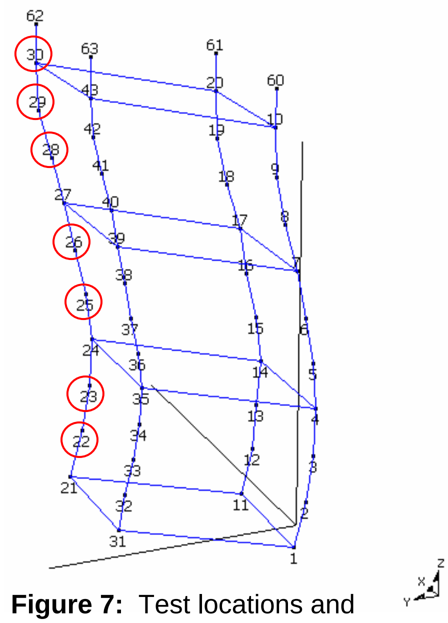
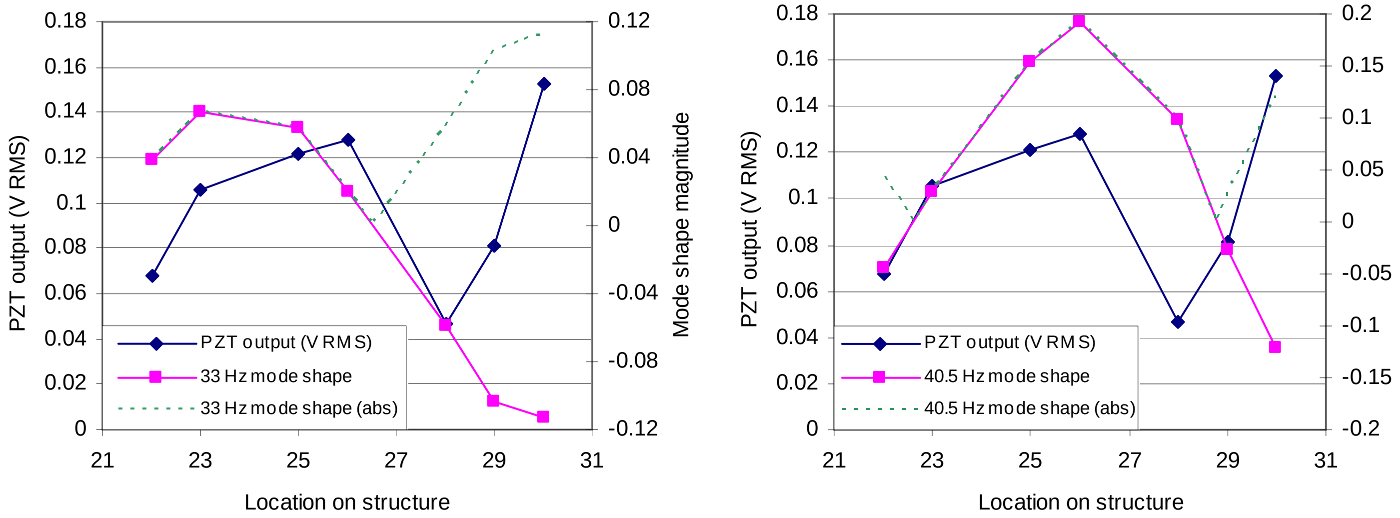


Figure 7: Test locations and deformed shape for 33 Hz mode



(a) 33 Hz beam output and 33 Hz mode shape

(b) 33 Hz beam output and 40.5 Hz mode shape

Figure 8: Relationship between output voltage from PZT on 33 Hz beam and mode shape magnitude.

The mode shape magnitudes were normalized before plotting. The mode shapes are included in Figures 8a and 8b to give a sense of the locations of nodes for the 33 Hz and 40.5 Hz modes by showing where the magnitudes change from positive to negative values or vice versa. For example, the 33 Hz mode has a node somewhere between points 26 and 28 on the structure.

The purpose of comparing PZT output and the absolute value of the mode shape, that is the mode shape magnitude, is to determine whether the two are directly correlated, that is, whether increases in the absolute value of the magnitude correspond to increases in the output voltage. The magnitudes have been normalized, so the individual magnitude values are not as important as the relation between one value to the other values in the set.

Note that the trend of the output from the 33 Hz beam only roughly follows the magnitude of the 33 Hz mode shape. For example, the PZT output is at a local maximum at the 26Y measurement point, while the mode shape is near its minimum. A possible explanation for this behavior can be seen in Figure 8b, which compares the 33 Hz beam output to the 40.5 Hz mode shape. The 40.5 Hz mode has a maximum at the 26Y location point and therefore a significant amount of energy is being input into the auxiliary structure at this frequency.

When the frequency response function of the PZT output measured at point 26Y is viewed, as shown in Figure 9, peaks are found at both 33 Hz and 40.5 Hz. The beam is clearly responding to both modes.

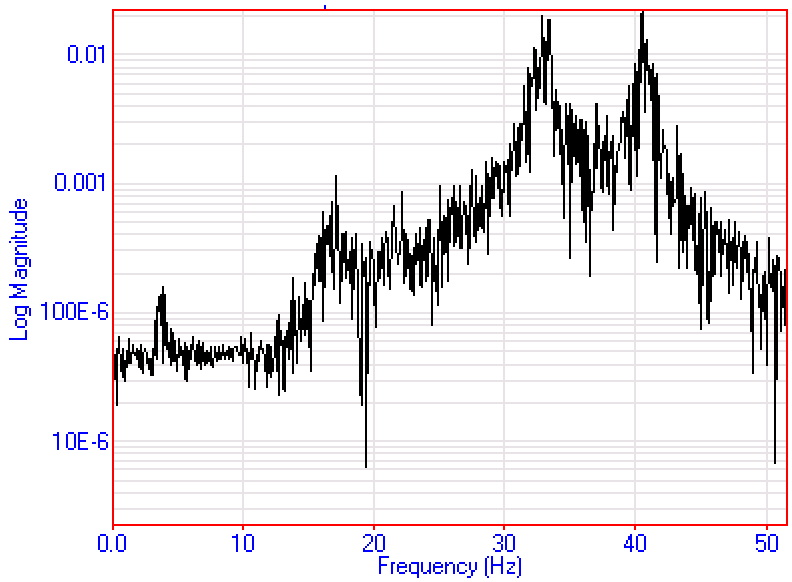


Figure 9: FRF of PZT output from 33 Hz beam, measurement point 26.

The beam tuned to 40.5 Hz was tested at five locations, as seen in Figure 10, and a similar result was obtained, as can be seen in

Figure **11**.

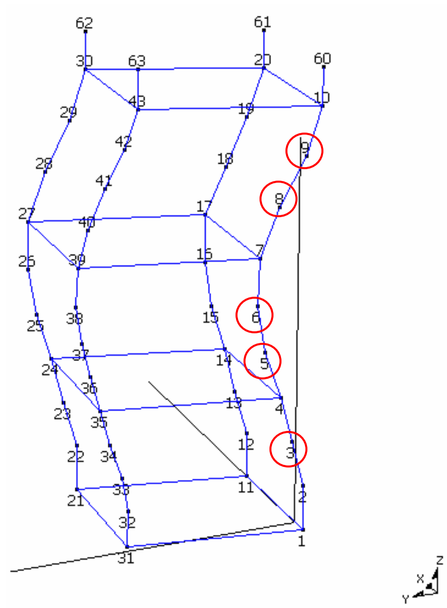
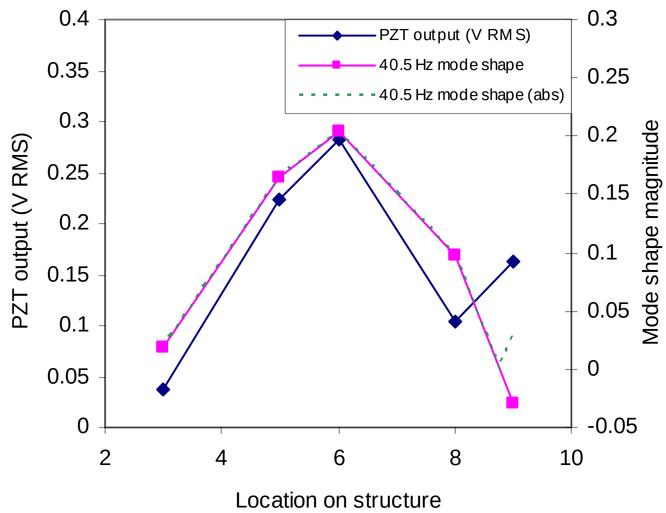
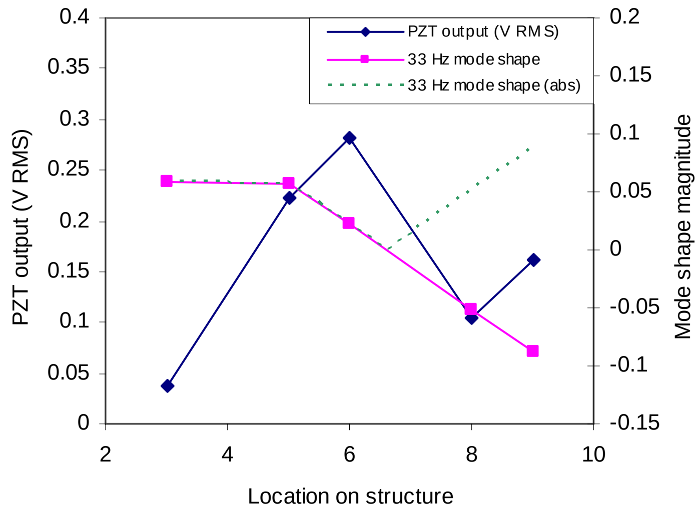


Figure 10: Test locations and deformed shape for 40.5 Hz beam.



(a) 40.5 Hz beam output and 40.5 Hz mode shape



(b) 40.5 Hz beam output and 33 Hz mode shape

Figure 11: Relationship between output voltage from PZT on 40.5 Hz beam and mode shape magnitude.

The response of the 40.5 Hz beam primarily follows the 40.5 Hz mode shape, except for the last measurement point (9Y). When the PZT output is compared to the 33 Hz mode shape, however, it can be seen that there is a maximum in the mode shape at that point. The FRF of the PZT output at point 9Y is shown below in Figure 12. Note that the PZT is primarily responding to the 40.5 Hz mode. However, there is also some response at 33 Hz. This is a possible explanation for the deviation of the PZT output from the 40.5 Hz mode shape magnitude.

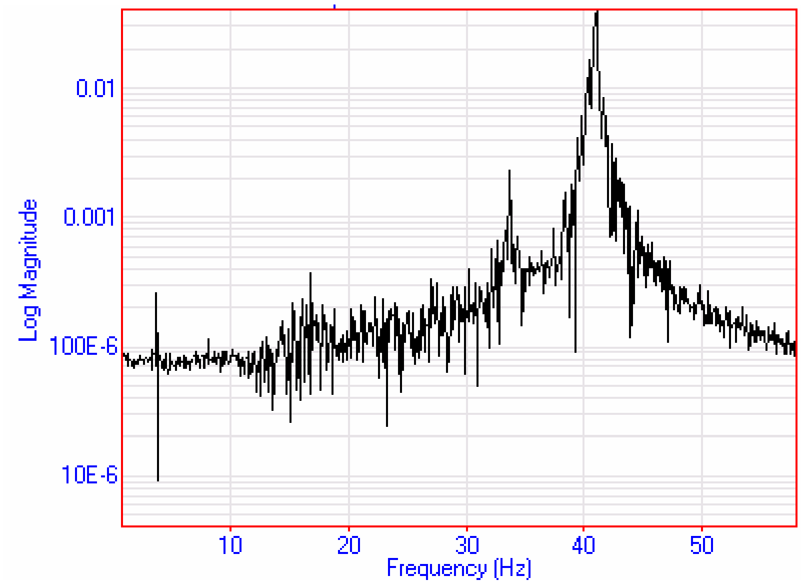


Figure 12: FRF of PZT output from 40.5 Hz beam, measurement point 9Y.

FUTURE WORK

This study did not conclusively determine how to optimize auxiliary structures in power harvesting. Additional tests must be conducted in order to quantify the relationship between the auxiliary structure's geometry and location, and the PZT output. More tests could also be conducted to determine the validity of Eq. (1).

The effect of the location of the PZT on the auxiliary beam must be investigated. The output should vary depending on the distance between the PZT and the column when the beam is attached to the structure. It is expected that the output will be greater when the PZT is closer to the column. For this study, however, the frequencies of the auxiliary beams were fine tuned by adjusting their free lengths, thereby changing the distance from the PZT to the column. It is recommended that the relative PZT location be studied independently of the other parameters.

An auxiliary structure tuned to a given frequency of the host structure responded both to this frequency and other nearby frequencies. The relationship between tuned mode shape magnitude and PZT output could therefore not be determined. In order to examine this relationship, the structure could be excited with a sinusoidal input at the tuned resonant frequency of the auxiliary structure. In that case, the response should be directly related to the mode shape magnitude, since the absorber should not be responding to other modes.

Series and parallel connections of PZT patches on the auxiliary structures should be explored. Each beam used in this study had only one PZT patch. A second patch could be easily attached to the other side of the beam, directly opposite the first patch. Connecting these two patches in series or in parallel could be useful in augmenting the output to reach power levels necessary for such applications as battery charging.

CONCLUSIONS

This study investigated the optimization of tuned cantilever beam auxiliary structures for power harvesting using piezoelectric materials. The auxiliary structures were attached to a host structure, which was then excited with white noise. Different types of auxiliary structures, tuned to different natural frequencies of the host structure, were attached to various points on the host structure to (a) examine the capabilities of the auxiliary structures to convert vibration energy to electrical energy and (b) determine how to optimize various parameters of the auxiliary structures for power harvesting. The following conclusions can be drawn from this study:

1. In general, tuned auxiliary structures harvest more power than mistuned auxiliary structures. The difference can be as much as a factor of two for structures mistuned by as little as 2 Hz.
2. An auxiliary structure tuned to a particular resonant frequency of the host structure will also respond to other frequencies of the host structure. There is therefore not necessarily a direct relationship between mode shape magnitude of the tuned frequency and the open-loop voltage output for white noise input.
3. For uniform cantilever beam auxiliary structures with a given material and first natural frequency, our tests showed that more power was harvested for structures that were long and thick as opposed to those that were short and thin. Due to the limited number of tests however, no general conclusions should be drawn from this one observation.
4. For an auxiliary structure with an end mass and a given material and first natural frequency, it was found that more power was harvested using the thinner auxiliary structure.

It should be recognized that some variability was introduced into the data due to the placement of the PZT patches on the auxiliary structures. Achieving the desired resonant frequency required adjusting the free length of the beams so that when they were clamped onto the host structure, the distance between the PZT and the column varied somewhat. This could be a significant source of error, and the effect of PZT location on performance should be investigated further.

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